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# Steady-State Ultrasonic Non-Destructive Evaluation for Aerospace & Additive Manufacturing Applications

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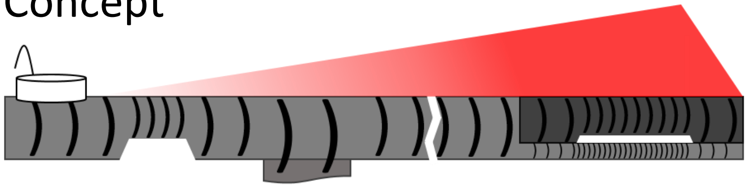
April 2, 2021

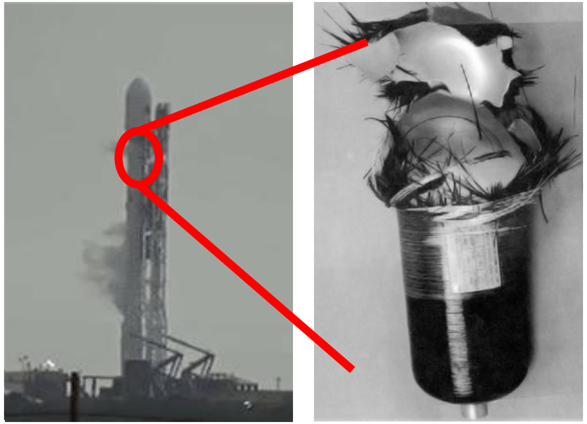
LA-UR-XX-XXXXX

# What are we talking about today?

## Steady-State Ultrasonic Inspection Concept



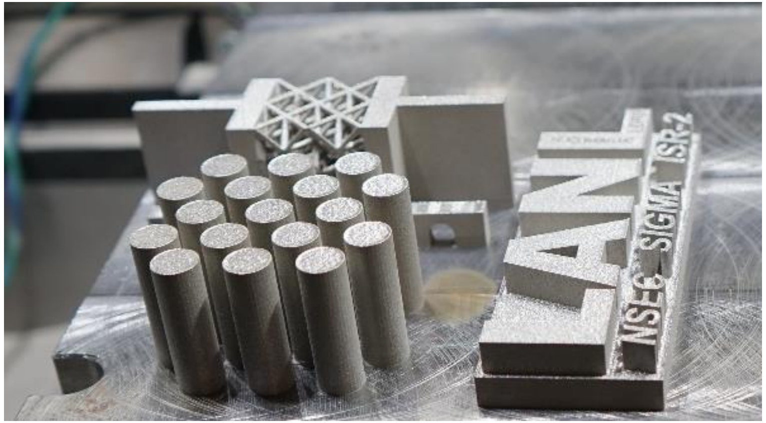
## Composite Overwrapped Pressure Vessels (COPVs)



US Launch Report (2016), Spaceflight101.com (2016)

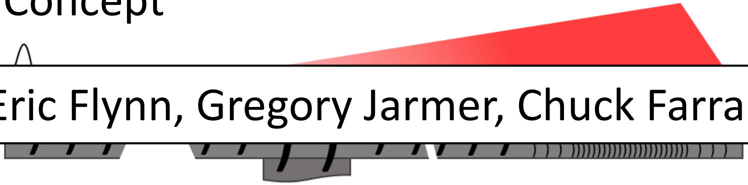
McLaughlan *et al.* (2011)

## In-Situ Direct Part Inspection for Additive Manufacturing



# Before we get started…credit where it's due!

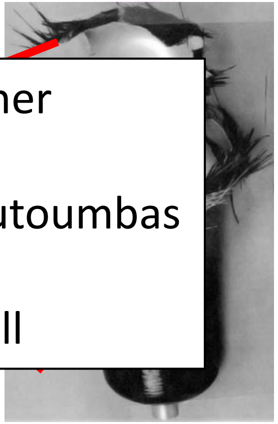
Steady-State Ultrasonic Inspection Concept



Eric Flynn, Gregory Jarmer, Chuck Farrar

Composite Overwrapped Pressure Vessels (COPVs)

US Launch Report (2016), Spaceflight101.com (2016)



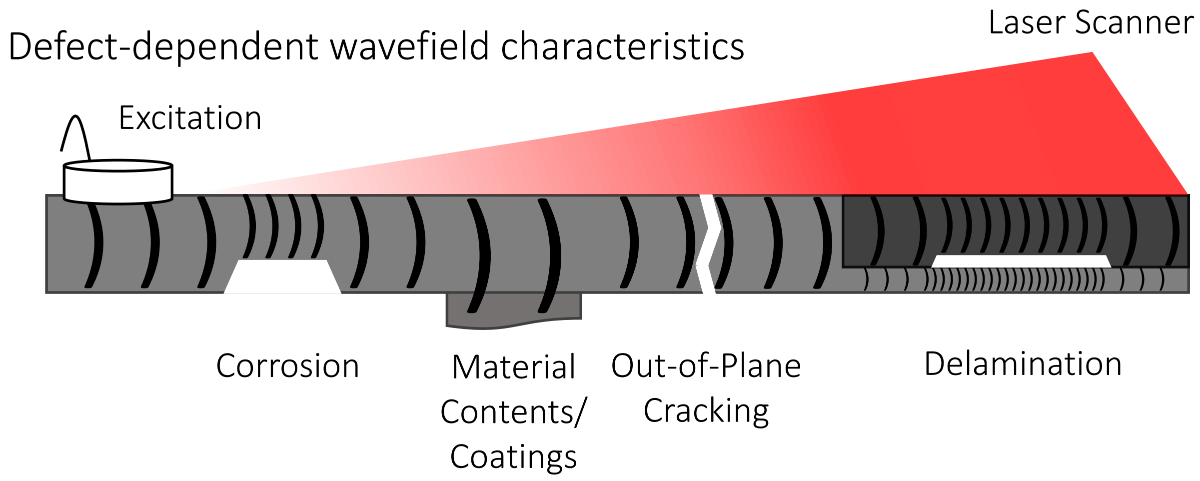
McLaughlan *et al.* (2011)

Casey Gardner
Young Ko
Michael Koutoumbas
Eric Flynn
Phil Cornwell

In-Situ Direct Part Inspection for Additive Manufacturing

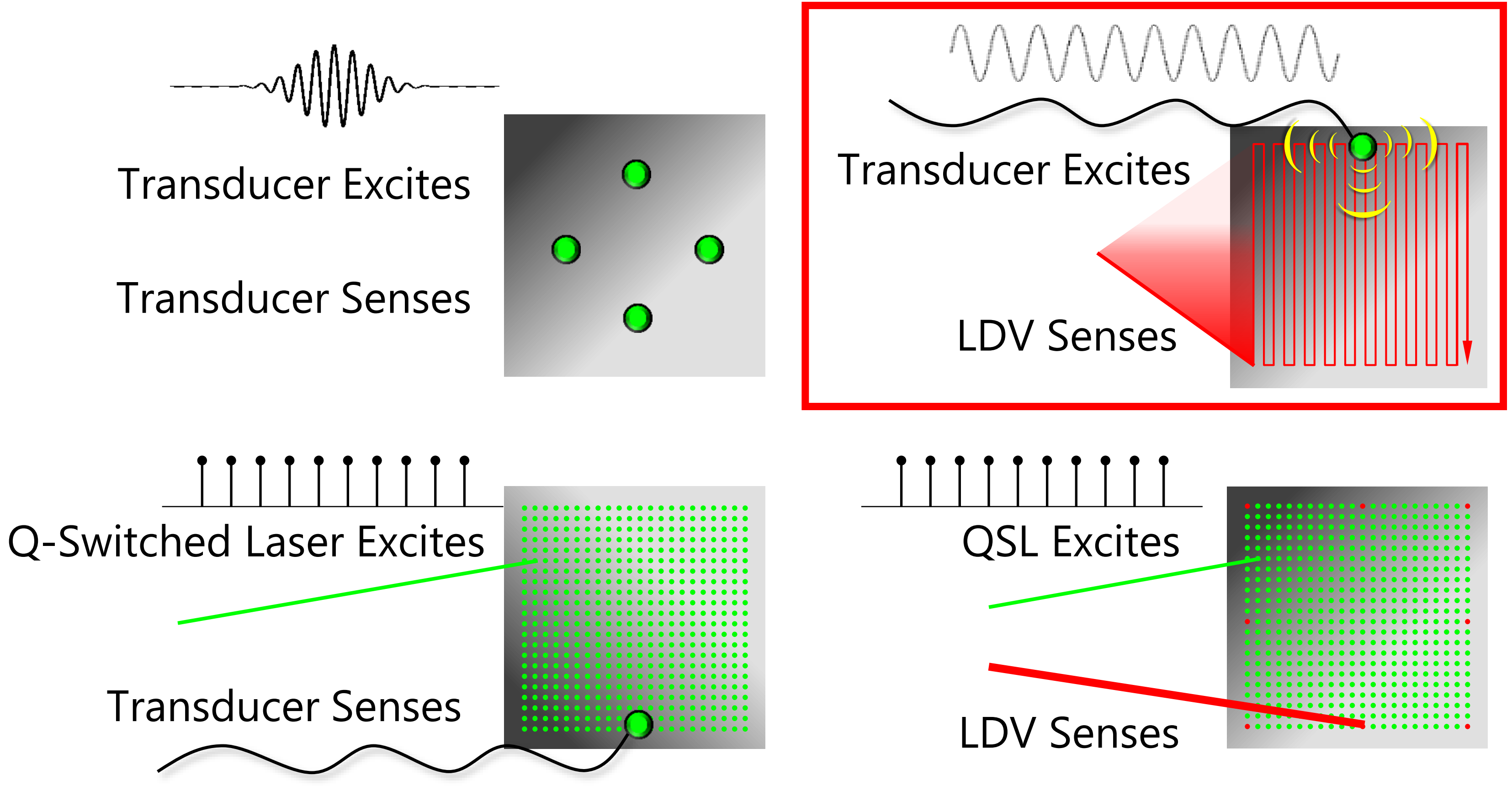

Erica Jacobson
Adam Wachtor
Eric Flynn

# How does ultrasonic inspection work?

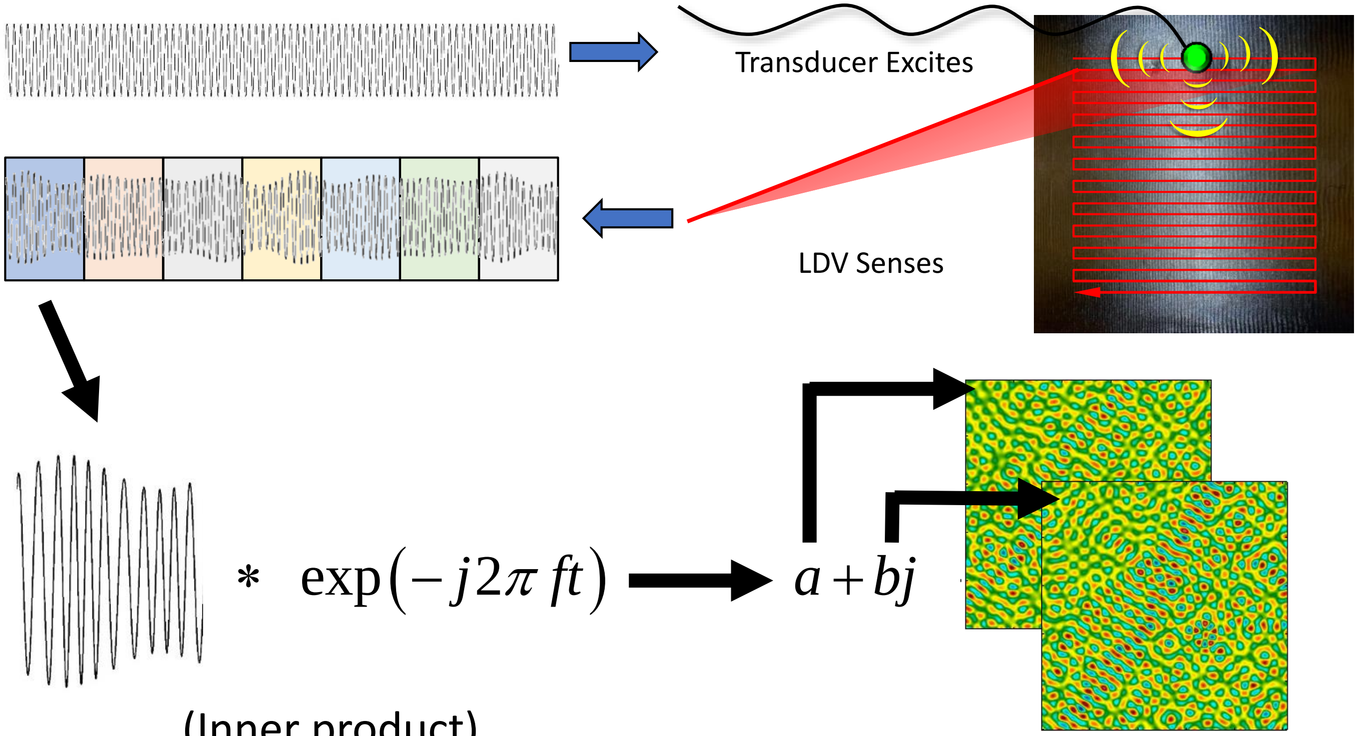



- Rich phenomenology of interactions between ultrasonic waves and features in plate-like structures
- Hidden defects/discontinuities create measureable changes in the surface wavefield
- Based on these measurements, we can build tools that:
  - Detect the presence of different kinds of defects
  - Estimate structural/material properties (e.g. local thickness)

# What are our options for guided wave ultrasonic inspection?



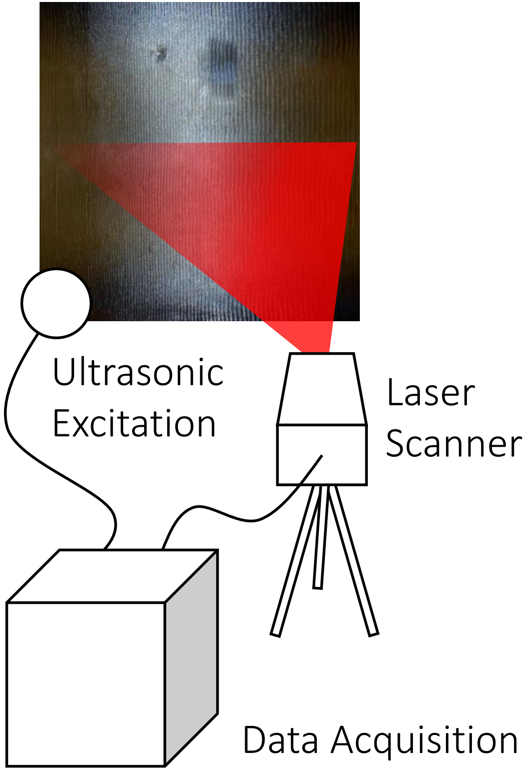
# How does steady-state ultrasonic inspection work?



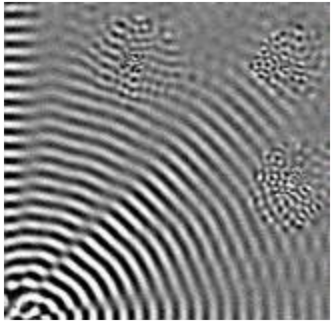

(Inner product)

# How does steady-state ultrasonic inspection work?

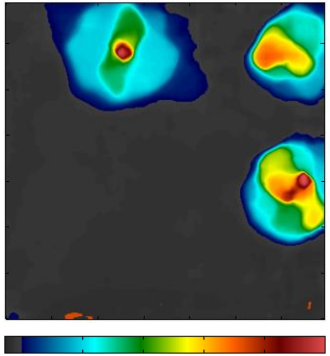
Inspection System




Wavefield Image



Defect Indicator



Typical Workflow for New Applications:

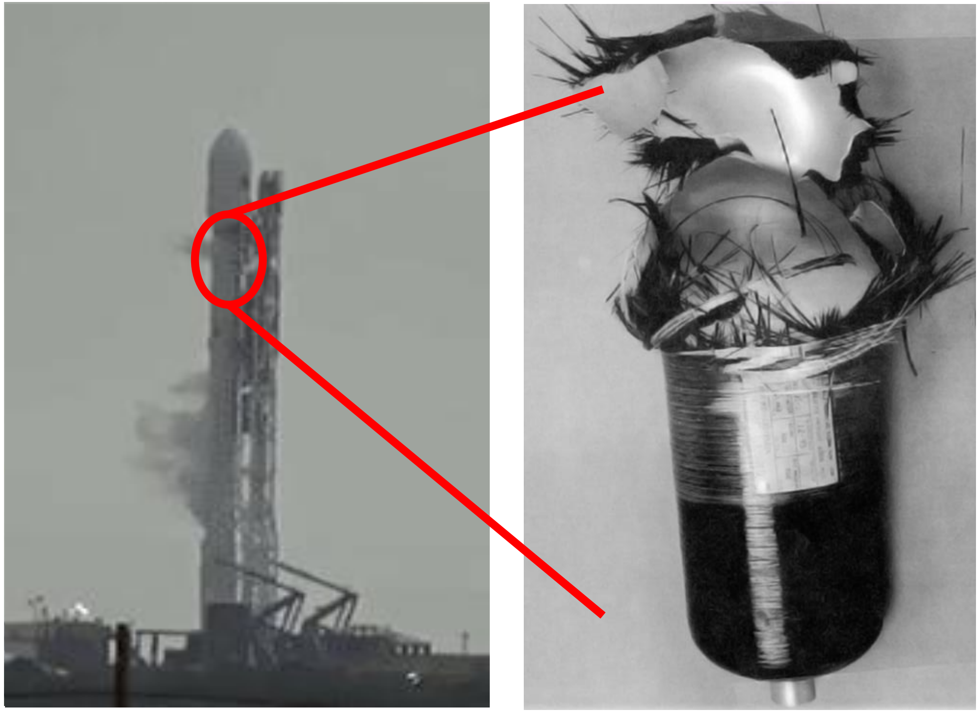
Hypothesize Phenomenology

To the Data!

Build a Detector/Estimator

# Questions So Far?

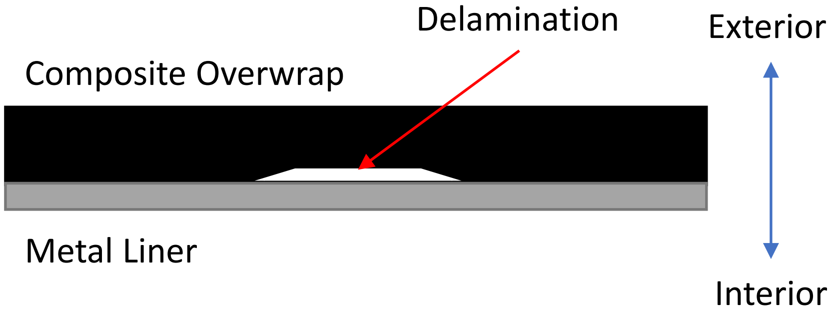
# COPVs: Why do we care?

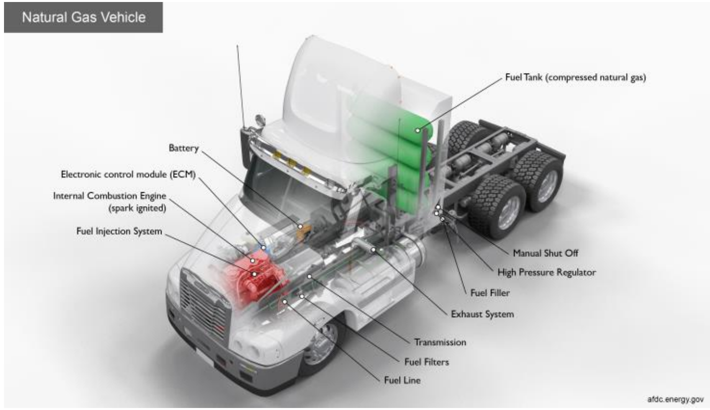


US Launch Report (2016), Spaceflight101.com (2016)

McLaughlan *et al.* (2011)

Cross-Section View:

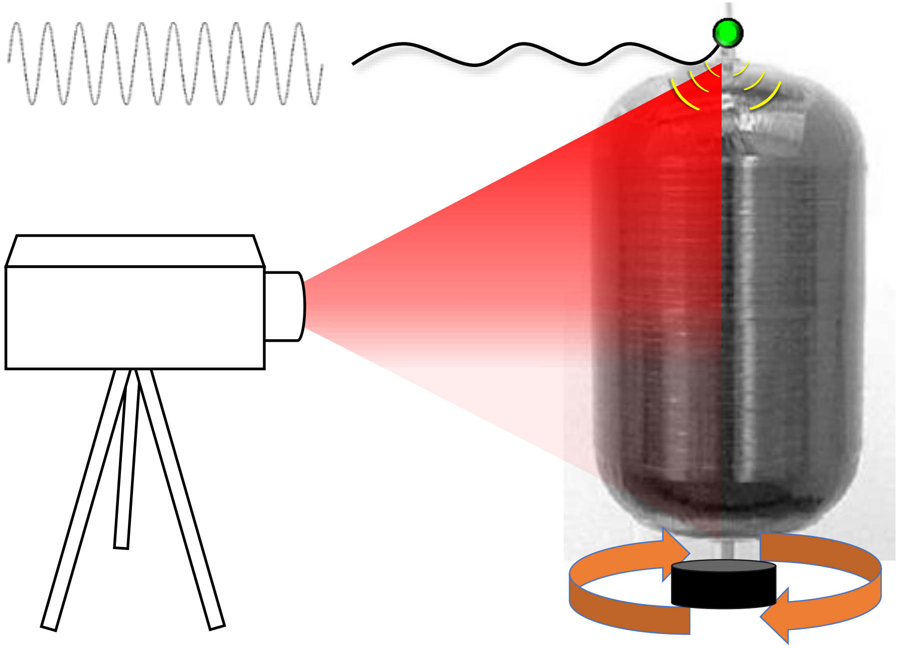



[https://afdc.energy.gov/vehicles/how-do-natural-gas-class-8-trucks-work]

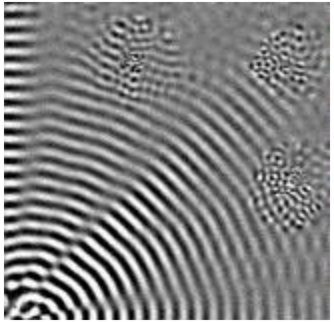
# The new shape requires a different scanning approach.

1) Stationary transducer excites with a single tone (~100 kHz)

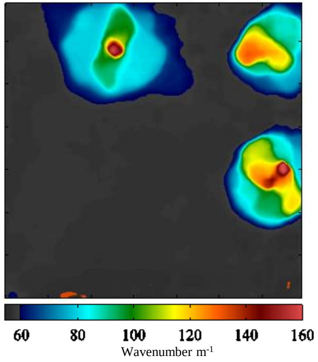


2) Laser Doppler vibrometer senses full-field response along a vertically swept line

3) Rotation stage rotates vessel to next vertical swept line position



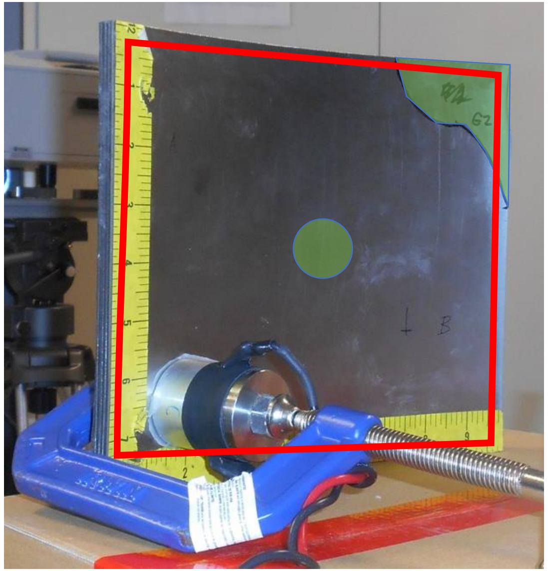
4) Scan lines are stitched together to form circumferential response map



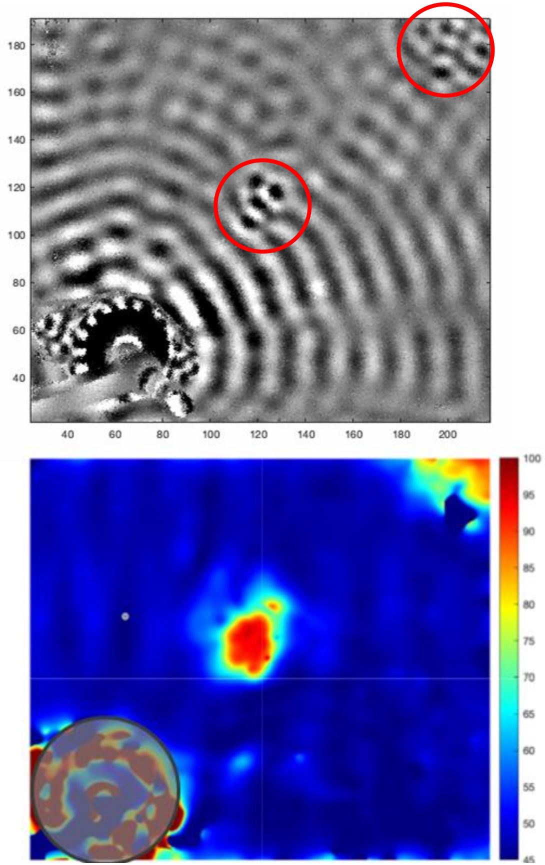

5) Estimate ultrasonic wavelength at each pixel to reveal regions of disbond/delamination

**Total inspection time ~ 1 min/m$^2$**

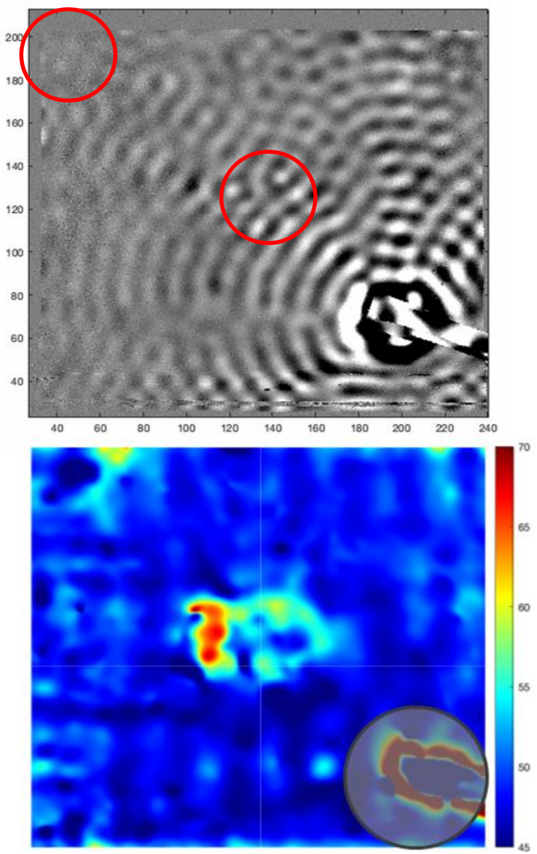
# The thickness of composite layers makes it difficult for ultrasonic wavefield imaging methods to locate damage.



**Metal Side**

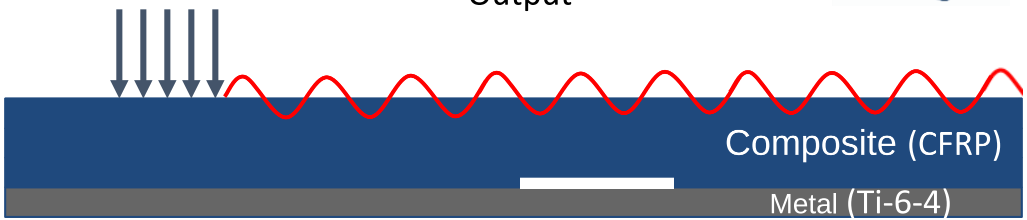



**Composite Side**

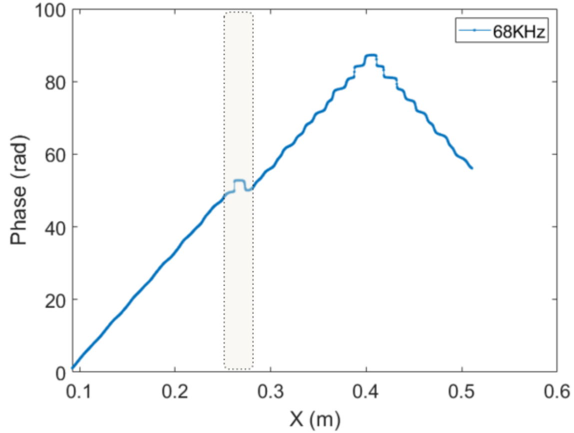


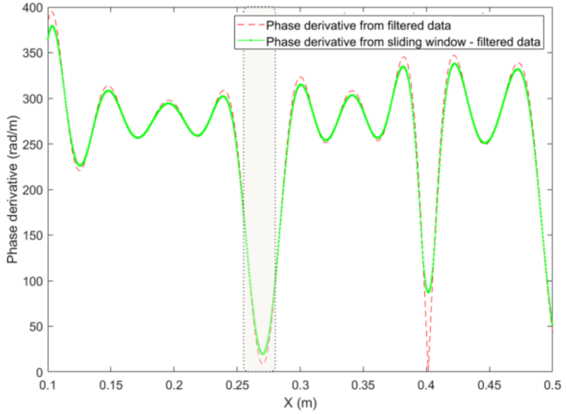

In practice, you can only scan the composite side, but it is difficult to locate delamination with traditional wavenumber processing in those datasets

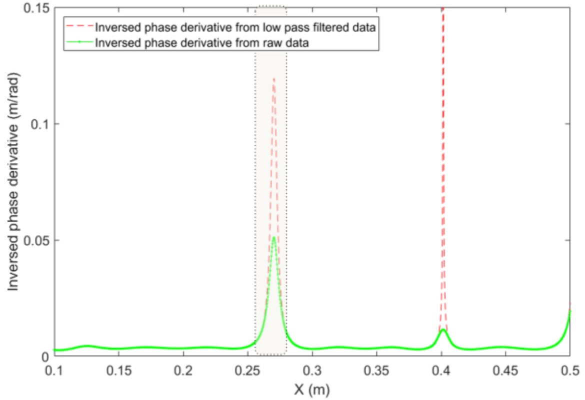
# At certain frequencies, local phase plateaus in the delaminated region.




## Low-pass Local Phase Derivative (LLPD)



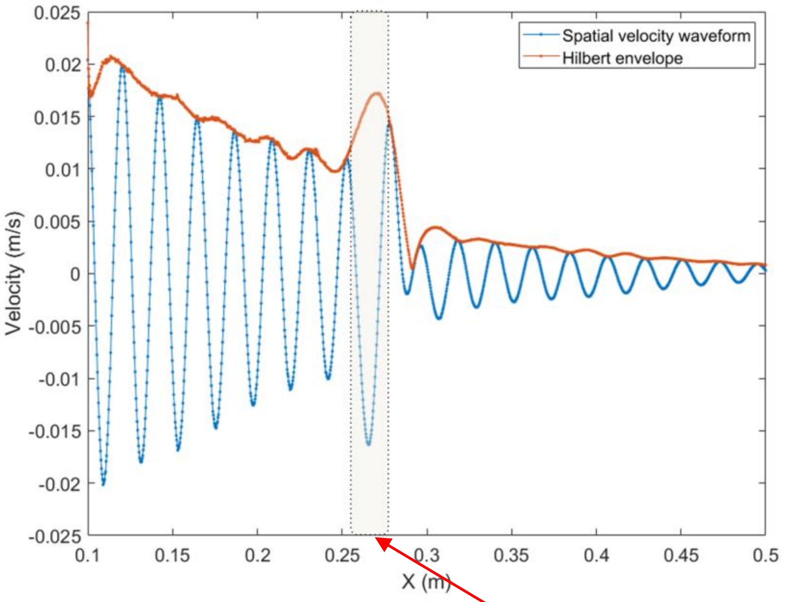



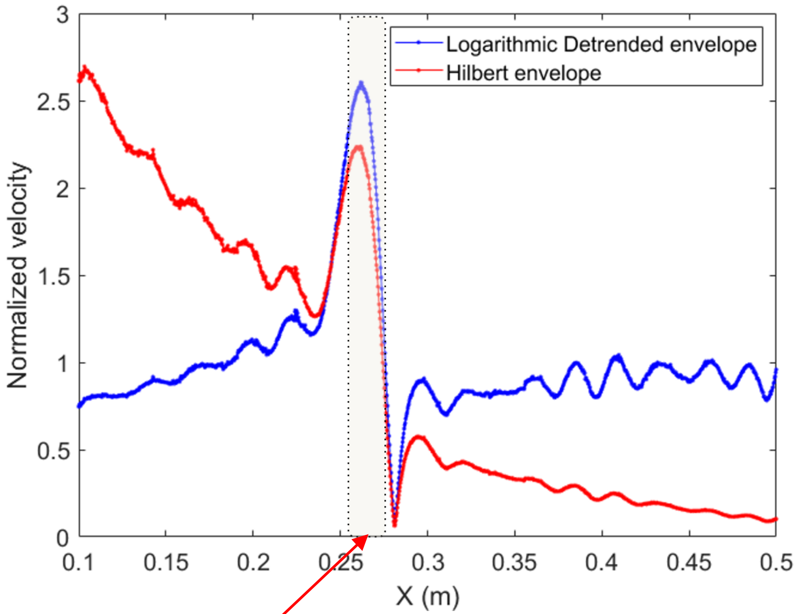




$$\widehat{\frac{d\phi}{dx}} = \frac{1}{N}\sum_{i=0}^{N-1} |\phi_{LPF}(x_{i+1}) - \phi_{LPF}(x_i)|$$

# At certain frequencies, the magnitude of the velocity spiked in the delaminated region.

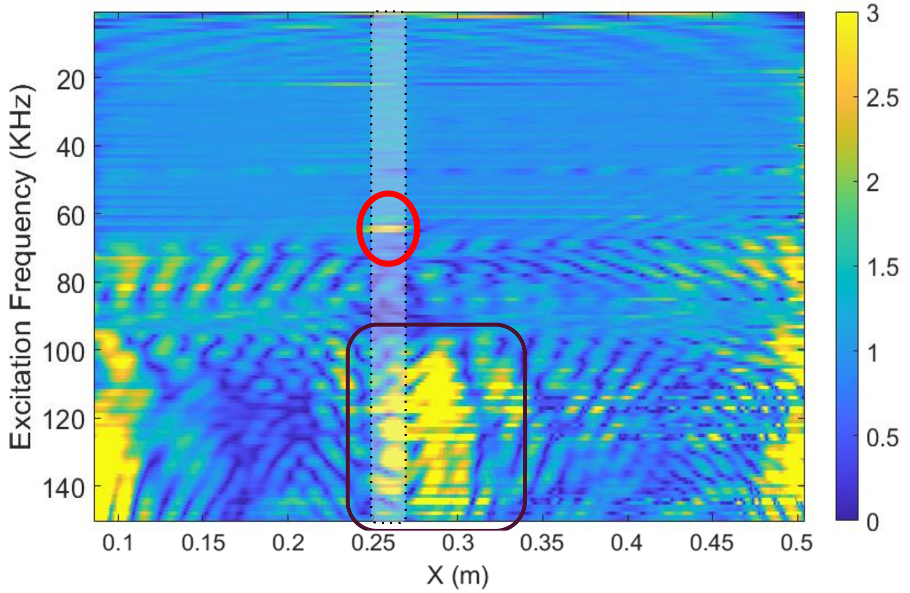
De-trended Hilbert Envelope Magnitude (DHEM)

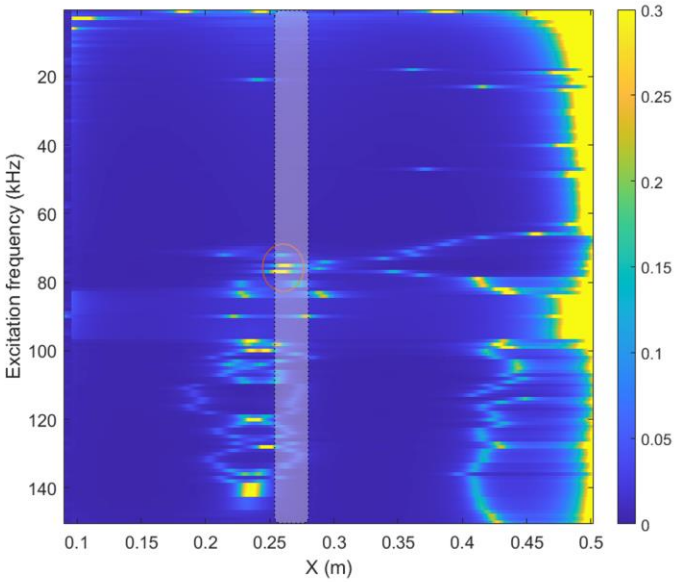



Delaminated Region

# We explored the effectiveness of the two features across a range of excitation frequencies.



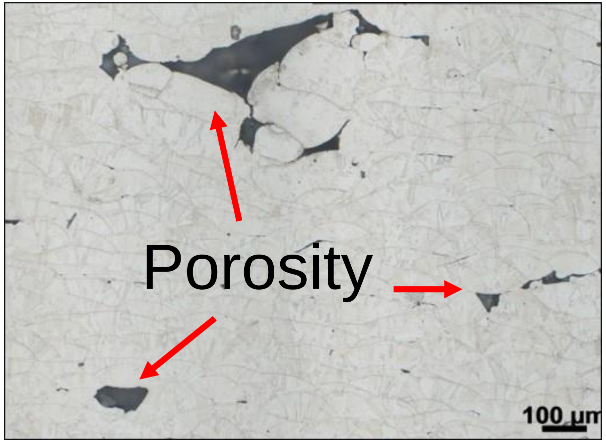

The effectiveness of these features is frequency dependent, which is also likely related to delamination size

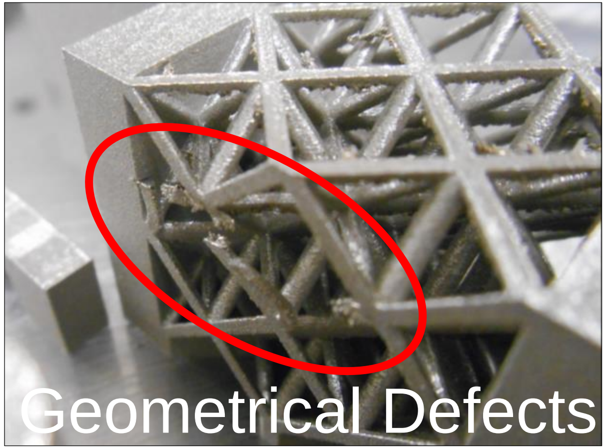
# Questions So Far?

# In-Situ Direct Inspection of Additively Manufactured Metal Parts

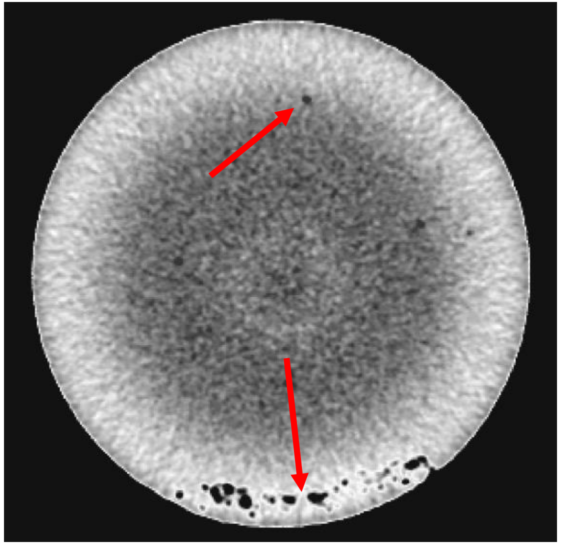


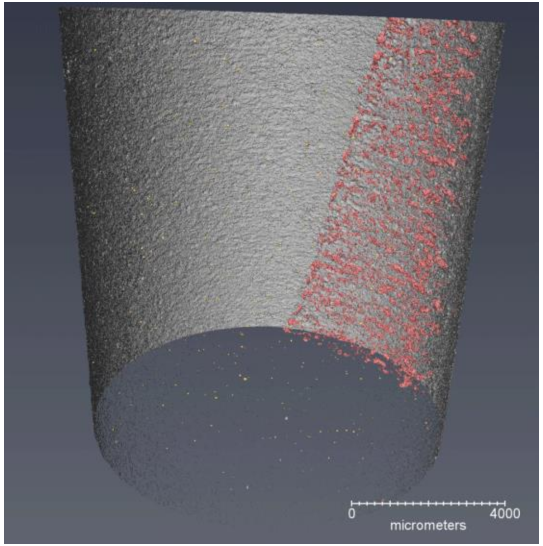
# Why do these parts need to be inspected?




State of the Art: X-Ray Computed Tomography (XCT)





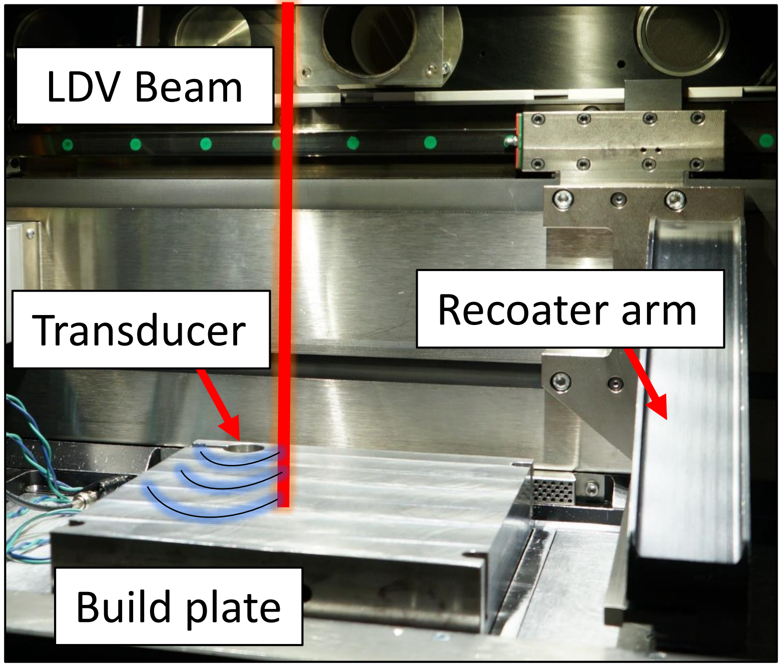

Ex-situ

Scans take time

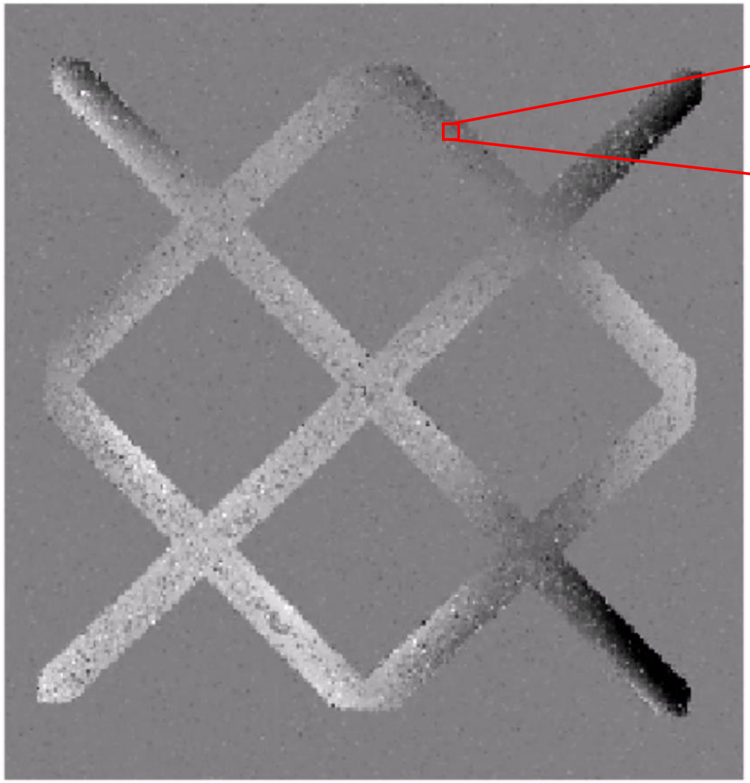
Limited to Small Parts

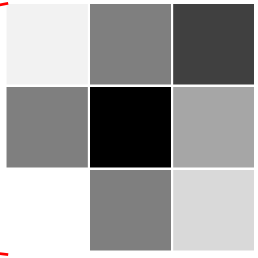
Internal Features Obscured

# In-situ Ultrasonic



# We can use In-situ Ultrasonic inspection measurements to detect as-built geometry.





Sort

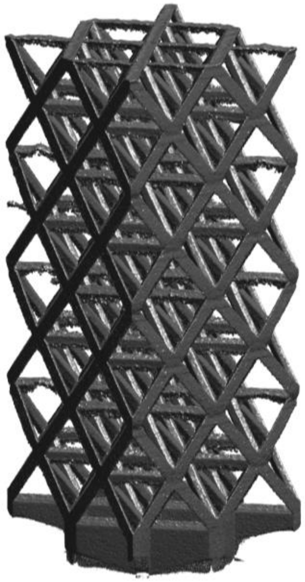
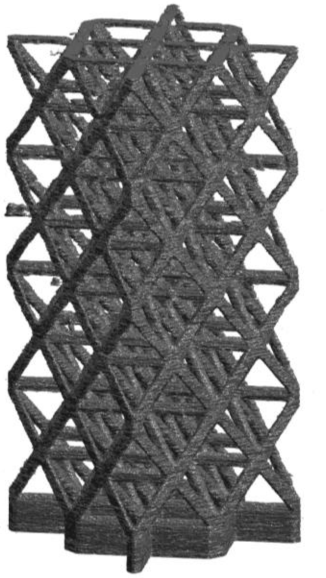
$$y = \mathbf{w}^T (\quad)$$

y > 0, solid

y < 0, powder

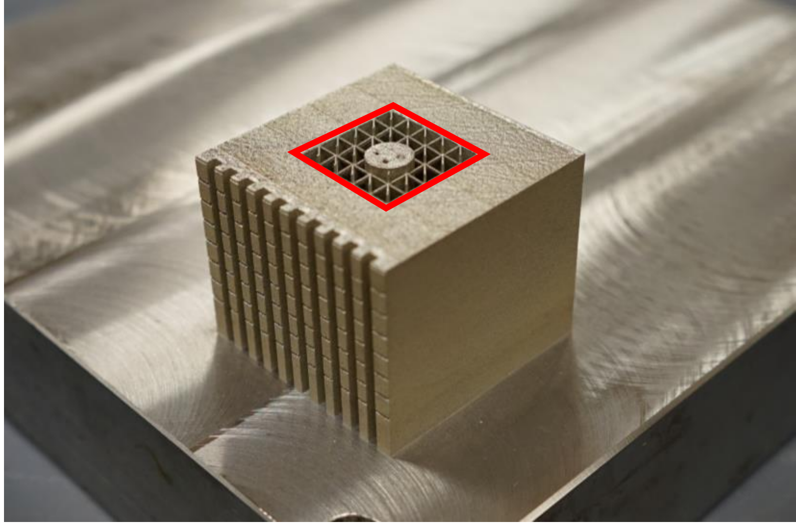
- Inspired by automated Ordered-Weighted Average weight learning
- Weight vector can express many familiar statistics (min, median, max, mean, trimmed mean, etc.)
- Learn optimal weight vector automatically using SVM

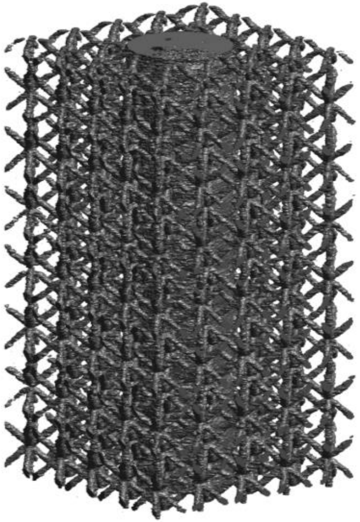
# How do XCT and In-situ Ultrasonic inspection stack up?

| | XCT | In-situ Ultrasonic |
|---|---|---|
| |  |  |
| Measurement Time (hours) | 4.5 | 1 |
| Measurement Resolution (µm) | 13.6 | 100 |
| Direct Mechanical Measurement? | No | Yes |

# In-situ ultrasonic inspection presents several key advantages.

- In-situ quality control inspections
  - Complex parts (e.g. concealed lattice)
  - Large parts
  - Faster measurement time
- Even more possibilities with full machine integration (e.g. alert the operator of defects, adjust build parameters)
- Future work:
  - More accurate geometry predictions that account for the multilayer nature of the sintering process
  - Detecting porosity





# Thank you!

Erica Jacobson[1], Eric Flynn[2], Adam Wachtor[1],
Casey Gardner[1*], Young Ko[1*], Michael Koutoumbas[1*], Phil Cornwell[3]

[1]National Security Education Center – Engineering Institute, LANL
[2]Intelligence and Space Research Division – Space and Remote Sensing Group, LANL
[3]Department of Mechanical Engineering – United States Air Force Academy
* (formerly)

Thanks to Brian Patterson and Lindsey Kuettner of LANL MST-7 for providing XCT data, and George T. (Rusty) Gray III of LANL MST-8 for providing porosity images!

*Research presented in this article was supported by the Laboratory Directed Research and Development program of Los Alamos National Laboratory under project number 20190580ECR.*

[1] https://www.eos.info/en/additive-manufacturing/3d-printing-metal/eos-metal-systems/eos-m-290
[2] https://www.sciencedirect.com/science/article/pii/S1359645417308170
[3] https://3dprint.com/wp-content/uploads/2015/03/Heat-Exchanger-landscape.jpg